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# Multiple and mass introductions from limited origins: genetic diversity and structure of *Solidago altissima* in the native and invaded range.

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8 **Multiple and mass introductions from limited origins: genetic diversity and structure of**

9 ***Solidago altissima* in the native and invaded range**

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15

16    **Abstract**

17    Understanding the origins and diversity of invasive species can reveal introduction and  
18    invasion pathways, and inform an effective management of invasive species. Tall goldenrod,  
19    *Solidago altissima*, is a herbaceous perennial plant native to North America and it has  
20    become a widespread invasive weed in East Asian countries. We used microsatellite and  
21    chloroplast DNA markers to obtain information on neutral processes and on genetic diversity  
22    in native and invaded populations of *S. altissima* and to infer how it invaded and spread in  
23    Japan. We found that introduced ( $n = 12$ ) and native ( $n = 21$ ) populations had similar levels of  
24    genetic diversity at nuclear SSR loci. Genetic structure analysis indicated that at least two  
25    independent colonization events gave rise to current *S. altissima* populations in Japan. The  
26    majority (68%) of the Japanese *S. altissima* were genetically similar and likely shared a  
27    common origin from a single or a small number of populations from the southern USA  
28    populations, while the populations in Hokkaido were suggested to arise from a different  
29    source. Our results suggest that multiple and mass introductions have contributed to the  
30    persistence and rapid adaptation of *S. altissima* promoting its widespread establishment  
31    throughout Japan.

32    **Keywords**

33    Genetic diversity · Invasion history · Microsatellite · Phylogeography · Population genetics ·

34    *Solidago altissima*

35



## 36 Introduction

37 Determining which factors enable exotic plants to proliferate in new environments is a  
38 fundamental challenge worldwide (Thuiller et al. 2005; Mitchell et al. 2006). The genetic  
39 variation in founder populations is a crucial factor in determining whether an invasive species  
40 will successfully adapt to their new locations (Lee 2002). Genetic variation can be introduced  
41 into a new geographic area either through multiple introductions of genotypes (Ellstrand and  
42 Schierenbeck 2000; Bossdorf et al. 2005; Kelager et al. 2013), or through introduction of a  
43 few pre-adapted genotypes with a broad range of physiological tolerance and phenotypic  
44 plasticity (Lee 2002; Dlugosch and Parker 2008; Yu et al. 2014).

45 Phylogeographical studies of invasive species using neutral genetic markers can retrace  
46 the possible routes of introduction, and determine the number of introductions, genetic  
47 variability of invasive and source populations, and the degree of hybridization among source  
48 populations of invasive species (Estoup and Guillemaud 2010; Handley et al. 2011;  
49 Fitzpatrick et al. 2012). This information will help determine the relative importance of  
50 stochastic and deterministic forces in determining the success of an invasive species (Lee  
51 2002; Lavergne and Molofsky 2007; Keller and Taylor 2008). The level of genetic diversity  
52 of exotic plants plays a key role in their ability to invade new areas (Lambrinos 2004;  
53 Dlugosch and Parker 2008; Keller and Taylor 2008; Vallejo-Marin and Lye 2013). Knowing  
54 the origins of invasive plants and how they spread is critical in designing strategies to control  
55 the colonization and spread of invasive plants (Roderick and Navajas 2003; Estoup and  
56 Guillemaud 2010).

57 *Solidago altissima* L. (Asteraceae), is a perennial herbaceous plant belonging to the  
58 *Solidago* subsect. *Triplinervae*. It is a dominant plant in the early stages of secondary  
59 succession in prairies, woodland edges, and old fields throughout North America in a broad  
60 geographic range (Semple and Cook 2006). It is among the most invasive introduced plants

61 in the East Asian countries of Japan, China, Korea, and Taiwan (Li 1978; Shimizu 2003;  
62 Huang and Guo 2004; Kil et al. 2004). In its native range, *S. altissima* occurs as diploid,  
63 tetraploid, and hexaploid ( $2n = 18, 36, 54$ ; Halverson et al. 2008). However, in Japan only  
64 hexaploids have been found (Sakata et al. 2013a). Semple et al. (2015) recognized three  
65 varieties of *S. altissima*. These varieties are associated with cytotypic variation, with *S.*  
66 *altissima* var. *gilvocanescens* reported as diploid and tetraploid, and *S. altissima* var.  
67 *altissima* and *S. altissima* var. *pluricephala* primarily as hexaploid with a few tetraploids  
68 reported at the western edge of their distribution and across the southeastern USA. *S.*  
69 *altissima* var. *altissima* and var. *pluricephala* occur from the eastern edge of the Great Plains  
70 to the Atlantic coast, while var. *altissima* are found predominately from 35° to 50° N latitude,  
71 *S. a. pluricephala* primarily south of 35° N latitude. *Solidago altissima* var. *gilvocanescens* is  
72 found in the Great Plains (Semple et al. 2015).

73 *Solidago altissima* was first introduced to Japan as an ornamental plant in 1897, but it  
74 was not until the 1980's that became naturalized throughout the country (Fukuda 1982), and  
75 it is still rare on the island of Hokkaido. *Solidago altissima* reproduces through obligate  
76 outcrossing via pollination by a wide range of insects (Melville and Morton 1982), and it  
77 produces large numbers of wind-dispersed seeds. Once established, it spreads almost  
78 exclusively through vegetative reproduction (Meyer and Schmid 1999). Two closely related  
79 species, *S. canadensis* L. and *S. gigantea* Aiton, have also become invasive throughout  
80 Europe (Weber 1997; Weber and Jakobs 2005). *Solidago altissima* has been studied for its  
81 phenotypic traits such as growth, allelopathic, and defensive traits in its invaded range in  
82 Japan (Ito et al. 1998; Sakata et al. 2014). Despite *S. altissima*'s status as a globally important  
83 invasive species, little is known about its invasion history, and how its genetic diversity has  
84 changed through the invasion process. Information of the invasion history would allow  
85 comparisons of phenotypic traits between native ancestors of the invasive populations and

allow inferences to be made about the evolution of plant traits in the invasive populations (Kellor and Taylor 2008).

In order to obtain information on genetic diversity in populations of *S. altissima* in both its native and invaded range, and to identify the source populations of lineages invasive in Japan to infer how it was introduced and spread in Japan, we studied the genetic diversity and structure of multiple *S. altissima* populations in their native and invaded ranges. We used both chloroplast DNA (cpDNA) markers and recently-developed nuclear simple sequence repeat (nSSR) markers, which differ in their mode of inheritance (maternal only vs. biparental) and mutation rate (higher at nuclear markers), and therefore give complementary insights into the invasion history and population dynamics (i.e., changes in size and age of populations) of the species.

## Materials and Methods

### Population sampling

Samples were collected from 20 populations of *S. altissima* from its native range in North America, and 11 populations from its invaded range in Japan, and one population in Korea during June to August in 2011-2013 (Table S1). In each population, samples of 10-24 (22.3 on average) leaves of *S. altissima* were collected from plants that were at least 5m apart. Because *S. altissima* in Japan are all hexaploid, we collected throughout the hexaploid range in the USA. Because of the possibility that hexaploid plants were derived from the hybridization between diploids and tetraploids plants after their invasion of Japan, diploid (CA: California, USA) and tetraploid plants (EF: Oklahoma, USA) were also collected to examine the genetic relationship among plants of different ploidy levels (Table S1). We determined the ploidy level of plants in the Midwestern USA since other ploidy level individuals occur sympatrically. We collected and cultivated rhizomes of 5 to 10 individuals

that we had used for leaf samples in the Midwest populations (HB, FB, CL, PE, CG, EF, I20, and HIL). Fresh leaf samples were collected from these cultivars to determine the ploidy levels by using chromosome counts, flow cytometry as described in Sakata et al. (2013a). In addition, allele numbers with nSSR genotyping were also used to determine the ploidy level of individuals without rhizome samples and plants in Korean populations. We also collected two individuals of *Solidago virgaurea* (subsection *Solidago*; from northern Honshu, Japan), 24 individuals of *Solidago gigantea* (subsection *Triplinerviae*; from Hokkaido, Japan), and six individuals of *Solidago canadensis* (subsection *Triplinervae*; from Jena, Germany) as outgroups. We collected larger number of samples of *S. gigantea* compared to other outgroup species to determine whether they have hybridized with *S. altissima* since they co-occur with *S. altissima* in the Hokkaido region in Japan.

#### DNA extraction and nSSR genotyping

Total genomic DNA was extracted from 1.0 cm<sup>2</sup> of plant tissue using a modified CTAB (cetyltrimethyl ammonium bromide) method (Milligan 1992). Fifteen nSSR markers out of 16 markers developed for *S. altissima* except for Salt 9 (Sakata et al. 2013b) were scored in all samples ( $N = 713$ ; Table S1). The nSSR loci were polymerase chain reaction (PCR) amplified following Sakata et al. (2013b) and loaded on an ABI Prism 3130 Genetic Analyzer (Applied Biosystems Foster City, California, USA), and scored using GENEMAPPER (Applied Biosystems). Of the 15 nSSR primer pairs, two loci (Salt 6 and 7) did not amplify well on the diploid population (CA) and *S. gigantea*. Therefore, the two loci were excluded from the analysis of outgroups and different ploidy level populations.

#### Chloroplast DNA sequencing

First, we screened cpDNA variation in intergenic spacers with 20 sets of PCR

primers from which six: *psbH-psbB*, *rps12-rpl20* (Shaw et al. 2005), *psbJ-petA*, *rpl-trnL*,  
*rps16-trnK*, and *trnQ-rps16* (Shaw et al. 2007) were selected due to amplification and  
variable sites and were sequenced for 142 samples (i.e., four samples per population and two  
samples per outgroup species). PCRs were performed on 20  $\mu$ L samples containing 50 ng of  
template DNA, 2  $\mu$ L of 10 $\times$ PCR buffer, 1.6  $\mu$ L of 2.5 mM dNTP, 0.1  $\mu$ L of 50  $\mu$ M each  
primer and 0.5 unit of TaKaRa Ex Taq<sup>TM</sup> (TaKaRa, Shiga, Japan). The PCR cycle for all six  
fragments was as follows: template denaturation at 94 °C for 3 min, followed by 35 cycles of  
denaturation at 95 °C for 1 min, annealing at 50 °C for 1.5 min and extension at 72 °C for 1.5  
min; followed by a final extension of 72 °C for 7 min. PCR products were sequenced using  
reverse primers with ABI Prism BIGDYE Terminator Cycle Sequencing Ready Reaction kit  
v. 3.1 (Applied Biosystems), and electrophoresed on an ABI Prism 3130 Genetic Analyzer  
(Applied Biosystems).

#### Genetic diversity, differentiation, and demographic analysis

For nSSR analysis, it was not possible to determine genotypes and allele  
frequencies from peak heights due to the high ploidy level. Therefore, only genetic diversity  
statistics that are not affected by genotype ambiguity were calculated. The number of  
maximum alleles per locus ( $A'$ ), Shannon diversity index (*Shannon*), and genetic  
differentiation statistics  $G'_{ST}$  (Hedrick 2005) were calculated at each nSSR locus using the  
software GenoDive 2.0b19 (Meirmans and Van Tienderen 2004) and POLYSAT v. 1.3-2  
(Clark and Jasieniuk 2011) in R v. 3.0.1 (R Development Core Team 2013). To measure the  
level of within-population genetic diversity, we calculated the following statistics: number of  
alleles per locus ( $N_a$ ), gametic heterozygosity ( $H_o$ ) (Moody et al. 1993), and Shannon  
diversity index (*Shannon*). Genetic differentiation statistics:  $G_{ST}$  (Nei 1973),  $G'_{ST}$  (Hedrick  
2005), and  $D_{EST}$  (Jost 2008) were calculated per population per loci using GenoDive 2.0b19.

For cpDNA sequence, the number of haplotypes ( $H$ ), haplotype richness ( $H_R$ ) and  $G_{ST}$  were calculated using CONTRIB v. 1.02 (Petit et al. 1998).

To assess whether populations in the native and invaded regions experienced past population expansions, mismatch distribution analysis (Rogers and Harpending 1992) was performed using Arlequin v. 3.11 (Excoffier et al. 2005). This analysis detects past population expansions and declines by measuring the signature of molecular changes (i.e. the frequency distribution of pairwise nucleotide or restriction site differences) that follow population fluctuations. The sum of square deviations between the observed and expected mismatch distributions and the raggedness index of the observed distribution were used as statistics to validate fit of the models (Rogers and Harpending 1992; Harpending 1994).

We calculated pairwise genetic differences between individuals averaged over loci with POLYSAT (Clark and Jasieniuk 2011) using two distance measures appropriate for polyploids: a band-sharing dissimilarity index (one minus the similarity index in eqn 1 of Lynch (1990)) and a measure taking into account mutational distance between microsatellite alleles (Bruvo et al. 2004). Because the hexaploid *S. altissima* is considered an autopolyploid (J. Semple personal communication), we calculated both Bruvo and Lynch distance matrices. We assessed the hierarchical partitioning of genetic variance within and among populations and between the two regions (native and invaded regions) by performing analysis of molecular variance (AMOVA) (Excoffier et al. 1992) on the basis of the two distance matrices using GENALEX 6.4 (Peakall and Smouse 2006). The same distance matrices were used to estimate pairwise  $\Phi_{pt}$ , an analogue of  $F_{st}$  (Weir and Cockerham 1984), between populations. Pairwise  $\Phi_{pt}$  were estimated using GENALEX 6.4 (Peakall and Smouse 2006). We also estimated pairwise  $\Phi_{pt}$  using the cpDNA sequence data. We tested for correlations between geographical and genetic distance [ $\Phi_{pt}/(1-\Phi_{pt})$ ] following a classical isolation by a distance method in each region using Mantel tests performed with GENALEX 6.4 (Peakall and

186 Smouse 2006).

187

188 Population genetic structure

189 Both flow cytometry analysis and nSSR genotyping indicated that the outgroup  
190 population CA (California, N°39.43, W°120.24) consists of diploid plants and population  
191 EF (Oklahoma) consists of tetraploid plants, and that all other populations were hexaploid. To  
192 clarify the genetic relationship with other taxa, we conducted a PCoA analysis based on  
193 Bruvo genetic distance matrices among outgroups (*S. gigantea* 4X and *S. canadensis* 2X) and  
194 the different ploidy populations. In the PCoA analysis, we included five hexaploid  
195 populations (SN, KRF, CG, I20, PAa), including the same geographic areas as outgroups.  
196 Because our focus was on the invasion history of *S. altissima* in Japan, we only used the  
197 hexaploid populations for the rest of the population analyses with nSSR.

198 Population structure based on the nSSR markers was examined by both distance  
199 and model-based methods. We increased the probability of obtaining correct phylogenetic  
200 tree topology (Takezaki and Nei 1996) using pairwise genetic distances of Nei's  $D_A$  (Nei et al.  
201 1983), calculated among the 32 populations to construct a neighbor-joining tree (Saitou and  
202 Nei 1987) using package APE (Paradis et al. 2004) in R. The application of a simple  
203 branching tree model to data, however, can be problematic when systematic errors, such as  
204 inappropriate assumptions in the evolutionary model and sampling errors resulting from  
205 small numbers of observed loci, exists (Huson and Bryant 2006). Thus, to explore and  
206 graphically present these ambiguities, we also constructed a split network (Bryant and  
207 Moulton 2004) on the basis of a distance matrix of Nei's  $D_A$  (Nei et al. 1983) using  
208 SplitsTree4 v. 4.10 (Huson and Bryant 2006). We also used the recently developed  
209 Discriminant Analysis of Principal Components (DAPC), which is a multivariate analysis  
210 that describes clusters of genetically related individuals (Jombart et al. 2010) using adegenet



v. 1.3-4 (Jombart and Ahmed 2011) in R using presence–absence (binary) genetic data. To find an optimal number of clusters in our data, we used k-means clustering of the principal components and calculated the statistical fit of the data for a given k, using the function `find.clusters` in `adeigenet`. The optimal number of clusters in the data was determined using the `diffNgroup` option, which identifies sharp changes in the fit of models (measured using Bayesian Information Criterion) with different numbers of clusters. We used  $10^6$  iterations of the model to search for convergence and obtained the likelihood associated with each value of k between 1 and 20. Finally, PCoA analysis using a pairwise  $\Phi_{pt}$  matrix obtained from two distance matrices (Bruvo and Lynch) was conducted with `GENALEX 6.4` (Peakall and Smouse 2006). This method produces a few axes containing most of the genetic variation in the data set and separates the populations.

Genetic structure in native and invaded populations was investigated using two model-based Bayesian algorithms implemented in `STRUCTURE 2.3` and `TESS 2.3.1` (Pritchard et al. 2000; Durand et al. 2009). The `STRUCTURE` analysis aims to cluster individuals in  $K$  genetic groups, using the multilocus genotypes of individuals. We performed ten independent runs with different proposals for  $K$ , testing each possible  $K$  from 2 to 10 using 100,000 iterations after a burn-in period of 50, 000 iterations. All runs were conducted with the admixture model, assuming correlated allele frequencies (Pritchard et al., 2000; Falush et al., 2003) with prior information on the sampling location (Hubisz et al. 2009). To ensure convergence of the Markov Chain Monte Carlo estimates, the consistency of results was checked for the ten replicates performed for each value of  $K$ . The most probable number of clusters ( $K$ ) was then determined using the change in log likelihood of the data between successive values of  $K$ , as described in Evanno et al. (2005). Parameters in the method of Evanno et al. (2005) were calculated using the program `Structure Harvester v. 6.0` (Earl and vonHoldt 2012). Population genetic structure was also estimated using a spatial hierarchical



Bayesian algorithm implemented in TESS 2.3.1, which includes spatial prior distributions on the individual admixture proportions (Durand et al. 2009). We estimated the population structure within the samples using this algorithm by incorporating individual geographic covariates in the prior distributions on the admixture memberships. Ten individual simulations were run for each  $K_{\max}$  ( $K_{\max}$  2–10), with 10,000 burn-in steps followed by 20,000 Markov Chain Monte Carlo steps.

To identify genetic groups, for cpDNA sequence data, a spatial analysis of molecular variance (SAMOVA) was performed using SAMOVA 1.0 (Dupanloup et al. 2002). Based on a simulated annealing procedure, SAMOVA algorithm iteratively seeks the composition of a user-defined number of groups ( $K$ ) of geographically adjacent populations that maximizes the proportion of total genetic variance ( $F_{CT}$ ) as a result of the differences between groups of populations. We set the number of initial condition to 100 with  $K = 2-10$ .

#### Phylogenetic relationships

The chloroplast sequence data were edited and aligned using BIOEDIT v. 7.0.8.0 (Hall 1999) and GENEIOUS PRO, version 5.4.6 (Drummond et al. 2011). Variable sites are listed in Table S2. Phylogenetic relationships between cpDNA haplotypes were assessed using a median-joining network with *Solidago virgaurea*, *Solidago gigantea*, and *Solidago canadensis* as outgroups using NETWORK v. 4.6.0.0 (Bandelt et al. 1999). In addition, phylogenetic relationships between cpDNA haplotypes were assessed with MEGA version 3.1 (Kumar et al. 2004), with conducting 1,000 bootstrap replicates to test the robustness of clades in maximum-parsimony trees. We ran analyses excluding and including indels and mononucleotide repeat length variations and found that though the resolution did not change the inclusion of indels resulted in complicated haplotype networks and the phylogenetic trees that were difficult to interpret. We will report data from analyses excluding indels.

## Results

### Genetic diversity and differentiation

The number of alleles observed in the native and invaded range per locus varied 9 to 29 (18.3 on average) and 7 to 31 (15 on average), respectively (Table 1). Out of the 306 different alleles found across the whole data set, 69 were unique to the native and 19 to the invaded range (Table 2). In the population genetic analysis, we used only the values averaged for all loci (Table S1). The invaded populations had lower mean number of alleles per locus within populations and a lower Shannon diversity index, whereas the observed heterozygosity was higher than the native populations. The genetic differentiation was higher in the invaded range ( $G_{ST} = 0.03$ ) than the native range ( $G_{ST} = 0.011$ , which was also true with alternative estimators of genetic differentiation  $G'_{ST}$  and  $D_{EST}$  (Table 2).

The concatenated cpDNA sequence had a length of 4417 bp with 21 substitutions (Table S2). Among the 32 haplotypes found in the total data set, seven haplotypes were found in outgroups (H6 and H10: *S. virgaurea*, H7: *S. gigantea*, H19 and H20: *S. canadensis*, H31: diploid, H12: tetraploid). There were five haplotypes shared with both native and introduced ranges (H9, H24, H25, H26, and H30), two haplotypes unique to the introduced range (H5 and H23), and 20 haplotypes unique to the native range (Table 2, Fig. 1). Overall genetic differentiation was low in both ranges:  $G_{ST} = 0.24$  and  $0.27$  in the native and invaded range, respectively (Table 2). Haplotype richness was smaller in the invaded range (Table 2: 3.15 and 2.54 in native and invaded range, respectively).

Analysis of mismatch distributions, which shows a large increase between  $0_0$  and  $0_1$  (Table 2) revealed support for recent expansion in both ranges. Non-significant sum of square deviations (SSD) and the raggedness index (HRI) of the observed distribution indices were obtained for both ranges ( $P > 0.05$ ), while both indices and observed value of time since

divergence ( $\tau$ ) in the invaded region showed lower values than those in the native region (Table 2).

The AMOVA analysis showed little genetic differentiation among individuals between the two ranges (4 and 5%), while there was a large genetic differentiation among individuals within populations (85 and 82%). The genetic divergence between the invasive and native groups was significant (Table 3).

We found a weak but significant association between genetic and geographic distance with the cpDNA markers in the native range (Fig. S1a:  $R^2 = 0.02$ ,  $P < 0.001$ ), but a non-significant association in the invaded range (Fig. S1b:  $R^2 = 0.002$ ,  $P = 0.42$ ). With the two genetic distance matrices obtained with the nSSR analysis, significant association between genetic and geographic distance was found for both ranges (Fig. S1c-f; Native:  $R^2 = 0.15$  for Bruvo, and 0.16 for Lynch,  $P < 0.001$  for both; Invaded:  $R^2 = 0.17$  for Bruvo, and 0.26 for Lynch,  $P < 0.001$  for both), indicating genetic isolation by geographic distance.

#### Population genetic structure and phylogenetic relationships

The PCoA analysis, including other taxa that are outgroups and the different ploidy populations showed that all the taxa were clustered separately from each other, except for the tetraploid *S. altissima*, which partly overlapped with the cluster of the hexaploid *S. altissima* (Fig. S2). The neighbor-joining tree based on the genetic distance of Nei's  $D_A$  (Nei et al. 1983) showed distinct differentiation between the native and invaded populations, with the exception of the Hokkaido (SN) population that was rather closely related to native populations (Fig. 2). In the native range, the most closely related populations to the invaded range were the southern populations (LSa, LSb, FLa, FLb). The Midwest USA populations (CL, PE, CG, I20, HIL) were genetically differentiated from other USA populations (Fig. 2). Korean population (KY) was strongly genetically differentiated from the Japanese

populations as indicated by length of this terminal clade estimated to be much longer than that of other populations. The population network included many boxes where more than one split and was distinctly non-tree-like (Fig. S3), meaning ambiguity in applying a simple tree model to the data, although the genetic relationship between populations was almost the same as those shown in the neighbor-joining tree. The PCoA analysis appeared to reflect a native–invaded differentiation pattern on the first axis, and a north–south differentiation in the invaded range in the second axis. The southern populations (LSa, LSb, FLa, FLb) in the native range were most closely associated with the invaded populations (Fig. S4), in agreement with the neighbor-joining tree and the population network analyses.

The STRUCTURE analysis showed a clear peak in the modal value of  $\Delta K$  at  $K = 5$  as determined by the method of Evanno et al. (2005), indicating that the most likely number of ancestral gene pools is  $K = 5$ . A spatial hierarchical Bayesian clustering TESS analysis and the DAPC analysis produced five genetic clusters similar to the genetic clustering pattern of populations with STRUCTURE analysis, although the extent of genetic admixture between populations appeared to be slightly larger than estimated by STRUCTURE analysis (Fig. S5). It suggests that it is unlikely that there was any spurious clustering in the STRUCTURE analysis caused by spatial autocorrelation. The red cluster was dominant in all Japanese populations, except for Hokkaido (SN) and the two other northern Japanese populations. These three populations had very different compositions that characterized by an admixture of more than three gene pools (Fig 3b). The population in Korea (SY) was a distinct cluster. Native USA populations varied with the green cluster being dominant in the central Midwest populations (CL, PE, CG), while the northern Midwest (HB, FB) and Eastern populations exhibited a highly admixed composition dominated by the purple cluster (Fig. 3b). Only the southern USA populations (LSa, LSb, FLa) and populations in the Atlantic coast (PAa, PAb, MD, VS) had a significant proportion of the red cluster.

The phylogenetic structure among *Solidago* species investigated was shallow, and haplotypes were not grouped to species monophyletically (Figs. 1 and S6). The most frequently observed haplotype (H25) was the most common haplotype in both the invaded range and the native range. All haplotypes observed in the invaded range were closely related to H25 except for H5 (Figs. 1 and S6). In the SAMOVA analysis, the  $F_{CT}$  value was highest when the number of population groups was defined as three, and included the diploid population (CA) and the tetraploid population (EF) which were detected as a separate group. When these two populations were excluded, the  $F_{CT}$  value was highest when the number of population groups was defined as five, and continued to decrease as the number of groups increased. The five groups included two single-population groups and two groups containing two populations, and a large group containing the rest of the populations. However, these groups had no biological consequence.

## Discussion

### Relationships among species and ploidy levels

The genus *Solidago* is known for complex taxonomy and clear differentiation of the species is further complicated, not only by the occurrence of interspecific hybrids, but also because many species are polytopic with overlapping ranges, and several species have multiple cytotypes (Semple and Cook 2006). A recent phylogenetic study of *Solidago* species has revealed a single origin involving reticulate evolution and introgression in an allohexaploid *S. houghtonii* (Laureto and Barkman 2011). While Laureto and Barkman (2011) resolved relationships among *Triplinerviae* species using chloroplast DNA sequence data, Schlaepfer et al. (2008) could not distinguish between *S. gigantea* and *S. canadensis*, and found that some haplotypes were shared with more than one species. Similarly, our results of the cpDNA sequence data could not resolve relationships among *S. altissima*, *S. gigantea*, and *S.*

*canadensis*. This was consistent even when we included the indels in the DNA sequence for the analysis. We cannot deny the possibility of either incomplete lineage sorting or chloroplast capture by secondary contact, both of which are consistent with recent speciation (Twyford and Ennos 2012). On the other hand, using microsatellite markers, three species were clustered separately and were shown to be genetically distinct. These high-resolution markers can be used to distinguish among polyploid taxa, except for tetraploids and hexaploids.

# Genetic diversity and structure in the native range

In the native range, we found high genetic diversity in nSSR markers within populations (Table S1). The genetic structure of nSSR data analyses showed that Central Midwest populations (CL, PE, CG, I20, HIL) were genetically differentiated from the rest of the populations (Figs. 2 and 3b). This could be explained by one of the most commonly observed phylogenetic breaks in Eastern North America, which is between the two sides of the Mississippi Valley (Soltis et al. 2006; Jaramillo-Correa et al. 2009). In addition, the genetic differentiation between HB, FB and the other Midwest populations is likely to reflect the southern limit of the Laurentide Ice Sheet. However, since most of our samples are hexaploid plants and include only a few other ploidy plants, we need more diploid and tetraploid samples from other geographic range, to examine the evolutionary history of *S. altissima* in North America. Although the closely related species *S. gigantea* showed the possibility of glacial survival in different refugial areas and separate migration routes on opposite sides of the Appalachian Mountains (Schlaepfer et al. 2008), we did not find any genetic discontinuity in the Appalachian populations. The phylogeographic study of the *Solidago* subsect., *Humiles* suggested Holocene polyploid speciation supported by restriction of endemic polyploid taxa to post-glacial habitats (Peirson et al. 2013). In line with these

findings, the cpDNA sequence data showed no pattern in genetic structure among hexaploid populations and the mismatch distribution analysis suggested rapid expansion of the populations (Table 2, Fig. 3a). The significant isolation by distance in both nSSR and cpDNA markers (Fig. S1) shows that genetic differentiation is influenced by geography in North America, and that most subsequent gene flow seems mediated through pollen, as indicated by the much stronger among-population differentiation at cpDNA (only dispersed by seeds) than nDNA (dispersed by both seeds and pollen) markers (Table 2). Alternatively, this could simply reflect the difference in the effective population size between cpDNA and nDNA markers. From the results of the mismatch distribution analysis and the fact that the hexaploid *S. altissima* is likely to have multiple origins from different diploid lineages (Halverson et al. 2008), the hexaploid *S. altissima* in North America would have expanded its range recently and the genetic structure been largely shaped through post-glacial migration and gene flow.

#### Multiple and mass introductions in the invaded range

Many studies have documented that the founding population reduces genetic variation within population, relative to the source population, because of a reduction in population size during colonization (Henry et al. 2009; Okada et al. 2007; Dybdahl and Drown 2011). However, there is increasing evidence for similar or even higher levels of within-population genetic diversity in exotic populations. This is typically explained by high propagule pressure, multiple introductions or admixture in the introduced range of individuals from different sources (Bossdorf et al. 2005; Dlugosch and Parker 2008; Kelagar et al. 2013).

The low haplotype diversity and a few private alleles indicate that introduced populations came from a single or a few independent origins (Table 2 and Fig. 1). Moreover, the introduced populations with the red cluster representing 68% of the introduced sites in

Japan are genetically similar and likely share a common origin, indicating that a single or a few populations were particularly successful in colonizing the invaded range. This can also be suggested as a result of post-invasion selection of genotypes adapted in invaded regions. This scenario has been confirmed in many successful invasive species (Lee 2002; Lombaert et al. 2010). Despite the small numbers of private alleles in the invaded range, the difference between introduced and native populations was significant in the genetic structure analysis (Figs. 2, S2, and S4). This may be caused by dissimilarities in allele frequencies rather than allelic identities. Hence, it is likely that high propagule pressure at primary establishment (i.e., mass introductions from few sources) and substantial gene flow through obligate outcrossing and production of large amounts of wind dispersed seeds have co-founded the widely distributed red cluster. This is also indicated in the Korean SY population with the high  $F_{ST}$  value of the yellow cluster in STRUCTURE analysis. Although the SY population has genetically differentiated from the other invaded populations, it was most closely related to the northern Honshu populations (Figs. 2 and 3). We speculate that the SY population originated from a source in the northern region of Japan, rather than a separate colonization event from the native source.

Our study infers multiple colonization with at least two primary colonization events of *S. altissima* into Japan. The Hokkaido population (SN) was clustered with the native populations (Fig. 2) and thus was genetically differentiated from the other introduced populations in the population structure analyses (Fig. S5). Fukuda (1982) notes that the Hokkaido populations have been established more recently in Japan compared to other regions. The populations in Hokkaido are more likely derived from an independent colonization event rather than a range expansion from the Honshu populations. In addition, the northern Honshu region showed higher admixture and higher genetic diversity than southern Japan populations (Table S1 and Fig. 3). These results indicate that secondary



colonization and gene flow (shown in Honshu and Hokkaido clusters) have contributed to the maintenance of high genetic diversity within populations in the invaded range.

The results of the genetic structure analyses in nSSR showed congruent patterns by different methods (neighbor-joining tree, population network analysis and PCoA analysis), which showed that the introduced populations dominated by the red cluster were genetically most related to the South region in North America (LSa, LSb, FLa, FLb), where the highest genetic diversity was observed (Table S1, S2). However, populations in the Atlantic coast region (PAa, PAb, MD, VS) are also related to populations in the invaded range. Moreover, the cpDNA analysis showed that only two haplotypes (H9 and H25) were shared between the invaded region and South region in North America, while four haplotypes (H9, H24, H25 and H26) were shared with the central Midwest populations. Larger sample size for cpDNA analysis, and analysis with higher resolution markers are necessary to identify the origin of the Japanese populations.

#### Spatial genetic structure in the invaded range and invasive spread during invasion

While the isolation by distance was significant for both cpDNA and nSSR data in the native range, it was only significant for nSSR data in the invaded range. The population differentiation was higher in the invaded range than in the native range for nSSR data (Table 2), but when the Korean (SY) and the Hokkaido (SN) populations were excluded they showed similar low values in both ranges ( $G_{ST}$ , 0.011 vs. 0.014;  $G'_{ST}$ , 0.052 vs. 0.061;  $D_{EST}$ , 0.041 vs. 0.048 in native and invaded range, respectively). There are two possible explanations. First, the multiple introductions from distinct native sources to different regions in Japan (i.e., Hokkaido) may account for the larger population differentiation in the invaded region than in the native range. Second, substantial gene flow has been present and/or genetic drift has been weak in the invaded range. High admixture in the northern Honshu region also

suggests this. Gene flow is promoted by the fact that *S. altissima* invaded along railways and roads, which form a highly connected habitat. In addition, the high ploidal nature of the species may have mitigated the effect of genetic drift (Gaudeul et al. 2011). Asai (1970) reported that Japanese bee-keepers have transplanted the naturalized *S. altissima* as honey-bee food plants. It implies that range expansion in Japan occurred by a series of long-distance human-mediated dispersal commonly found in invasive species (Okada et al. 2007; Gaudeul et al. 2011; Kelager et al. 2013).

Our reconstruction of *S. altissima*'s invasion history based on historical records and the results of genetic diversity and structure in both range, suggests that the invaded populations arose from introductions from a few sources potentially in the southern part of North America in early 1900s by ornamental planting and commercial exchange. Later, the independent introduction from different native sources to Hokkaido generated admixture between genetic clusters leading to high genetic diversity in the northern region in Japan. Soon after, human-mediated dispersal and the high ploidal nature of the species contributed to the rapid and successful invasion. We summarize that multiple and mass introductions may have contributed to the persistence and rapid adaptation of the species enabling it to be spread throughout Japan. The high genetic diversity maintained within populations in the invaded range is often found in other polyploid plants (Schlaepfer et al. 2008; Hornoy et al. 2013; Vallejo-Marin and Lye 2013). High levels of heterozygosity (and nearly double the effective population size) compared with diploid plants are characterized by autopolyploids as a result of polysomic inheritance (te Beest et al. 2012). Furthermore, the fact that *S. altissima* is perennial may have also increased the effective population size as discussed in other systems (Hornoy et al 2013). Together with the growing number of studies of invasive polyploid plants, our results also emphasize the significance of considering polyploid as an important

trait in invasion models, as polyploids benefit from reduced genetic impact of bottlenecks,  
and a high evolutionary potential (Lee 2002; te Beest et al. 2012).

## Future directions

Determining the mechanisms underlying successful range expansions and rapid adaptive processes including genetic factors, environmental factors, or their interactions is a critical challenge. Closely related *Solidago* species exhibit latitudinal variation in phenology (Weber and Schmid 1998) and enhanced competitive ability (Yuan et al. 2012) in the invaded range. Our previous study on *S. altissima* in Japan showed that plant resistance was rapidly selected when it was re-associated with a recently invaded herbivorous insect, *Corythucha marmorata* from North America (Sakata et al. 2014). The present results support the argument that large genetic variability was introduced and local adaptation is ongoing in the invaded range. Direct ancestor-descendent comparisons of phenotypic traits between native and introduced populations (Kellor and Taylor 2008) will clarify whether the adaptation is a result of historical factors or of evolutionary changes involved in the invasion process (i.e., separating the role of stochastic and demographic events from that of selection in shaping the evolution of phenotypes), which is an important focus in future research.

Knowledge of the genetic variation in *S. altissima* in its native and invaded ranges can aid in the development of effective strategies to manage its spread. Information on the amount and distribution of genetic diversity can help to predict its response to chemical and biological control by considering the impacts of genetic variability on the interactions of the invasive species and the biological agents (Garcia-Rossi et al. 2003).

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Table 1. Characteristics of the 15 microsatellite loci examined in this study.

Locus	Native ( $N = 443$ )			Invaded ( $N = 270$ )		
	$A'$	<i>Shannon</i>	$G'_{ST}$	$A'$	<i>Shannon</i>	$G'_{ST}$
<i>Salt1</i>	26	2.66	0.146	21	2.31	0.357
<i>Salt2</i>	19	1.86	0.057	10	1.29	0.085
<i>Salt3</i>	28	2.83	0.128	31	2.49	0.307
<i>Salt4</i>	16	1.83	0.063	12	1.57	0.132
<i>Salt5</i>	29	2.46	0.076	21	2.09	0.164
<i>Salt6</i>	24	2.57	0.074	14	1.98	0.265
<i>Salt7</i>	13	1.29	0.018	13	1.28	0.191
<i>Salt8</i>	16	2.28	0.064	17	2.09	0.084
<i>Salt13</i>	13	2.01	0.025	7	1.78	0.068
<i>Salt14</i>	9	1.61	0.029	9	1.11	0.121
<i>Salt16</i>	15	1.49	0.021	17	1.08	0.083
<i>Salt17</i>	18	1.78	0.05	18	1.58	0.086
<i>Salt18</i>	18	1.95	0.079	12	1.59	0.066
<i>Salt19</i>	12	1.73	0.095	8	1.44	0.053
<i>Salt21</i>	19	2.01	0.048	15	1.72	0.123
Overall	275	2.88	0.052	225	2.67	0.126

$A'$ , number of maximum alleles per locus; *Shannon*, Shannon diversity (mean across population);  $G'_{ST}$ , standardized genetic differentiation index (mean across population) (Hedrick 2005).

Table 2.

Genetic diversity of cpDNA (upper half) and nSSR (lower half) analysis, and the results of the mismatch distribution analyses of the native and invaded populations of *S. altissima*.

	Native		Invaded
cpDNA			
<i>H</i>	25 (2X: H31, 4X: H12)		7
<i>H<sub>R</sub></i>		3.15	2.54
<i>G<sub>ST</sub></i>		0.238	0.272
SSD		0.087 (0.45)	0.064 (0.26)
HRI		0.401 (0.62)	0.319 (0.34)
tau		1.71	0.94
$\theta_0$		$4.2 \times 10^{-3}$	$2.9 \times 10^{-4}$
$\theta_1$		$5.8 \times 10^4$	$7.0 \times 10^4$
nSSR			
<i>N<sub>a</sub></i>		9.68	7.92
<i>A</i>		275	225
<i>H<sub>O</sub></i>		0.863	0.873
<i>P<sub>R</sub></i>		69	19
<i>Shannon</i>		2.88	2.67
<i>G<sub>ST</sub></i>		0.011	0.03
<i>G'<sub>ST</sub></i>		0.052	0.13
<i>D<sub>EST</sub></i>		0.041	0.099

*H*, number of haplotypes; *H<sub>R</sub>*, haplotypic richness; *G<sub>ST</sub>*, genetic differentiation index (Nei 1973); *SSD*, the sum of square deviations between the observed and expected distributions (Rogers and Harpending 1992); *HRI*, the raggedness index of the observed distribution

766 (Harpending 1994); **tau**, the time parameter to the population expansion; **θ<sub>0</sub>**,  $\theta$  before  
767 population expansion; **θ<sub>1</sub>**,  $\theta$  after population expansion, pairwise difference of population  
768 after growth; **N<sub>a</sub>**, number of alleles per locus per population; **A**, total number of alleles, **H<sub>o</sub>**,  
769 gametic heterozygosity (Moody 1993); **P<sub>R</sub>**, number of private alleles, **Shannon**, Shannon  
770 diversity; **G<sub>ST</sub>**, genetic differentiation index (Nei 1973); **G'<sub>ST</sub>**, standardized genetic  
771 differentiation index (Hedrick 2005); **D<sub>EST</sub>**, standardized genetic differentiation index (Jost  
772 2008).

773  $N_a$ ,  $H_o$ , Shannon,  $G_{ST}$ ,  $G'_{ST}$ , and  $D_{EST}$  are mean values across loci and population.

774 Values in parentheses in  $H$  represent haplotypes of diploid (2X) and tetraploid (4X) samples.

775 Values in parentheses in SSD and HRI represent  $P$  values.

776

777 Table 3. Results of the analysis of molecular variance for both ranges.

Distance measure	Source	d.f.	Variance Components	%	Fixation indices
Bruvo	Among range	1	0.010	4	$\Phi_{RT} = 0.039^*$
	Among population	30	0.027	11	$\Phi_{PR} = 0.113^*$
	Within population	681	0.212	85	$\Phi_{PT} = 0.148^*$
Lynch	Among range	1	0.012	5	$\Phi_{RT} = 0.047^*$
	Among population	30	0.035	13	$\Phi_{PR} = 0.138^*$
	Within population	681	0.218	82	$\Phi_{PT} = 0.179^*$

778

779

780  $*P < 0.0001$ , the probability of obtaining by chance an fixation indices equal to or greater

781 than the observed value, estimated from 999 permutations.

782



## Figure legend

### Fig. 1

The haplotype network of *Solidago altissima* based on chloroplast DNA sequence variation. Circle size is proportional to haplotype frequency. Each line between haplotypes corresponds to one mutational change. Small black squares indicate missing haplotypes. Haplotypes found in both native and invaded populations are shown in dotted outlines, and haplotypes only found in invaded populations are shown in diamonds, and haplotypes of outgroup species are shown in triangles: *S. virgaurea*, H6 and H10; *S. gigantea*, H7; *S. canadensis*, H19 and H20.

### Fig. 2

A neighbor-joining tree summarizing the relationships among hexaploid *S. altissima* populations based on Nei's genetic distance (Nei et al. 1983). \* Populations in the invaded range. Abbreviations refer to Table S1.

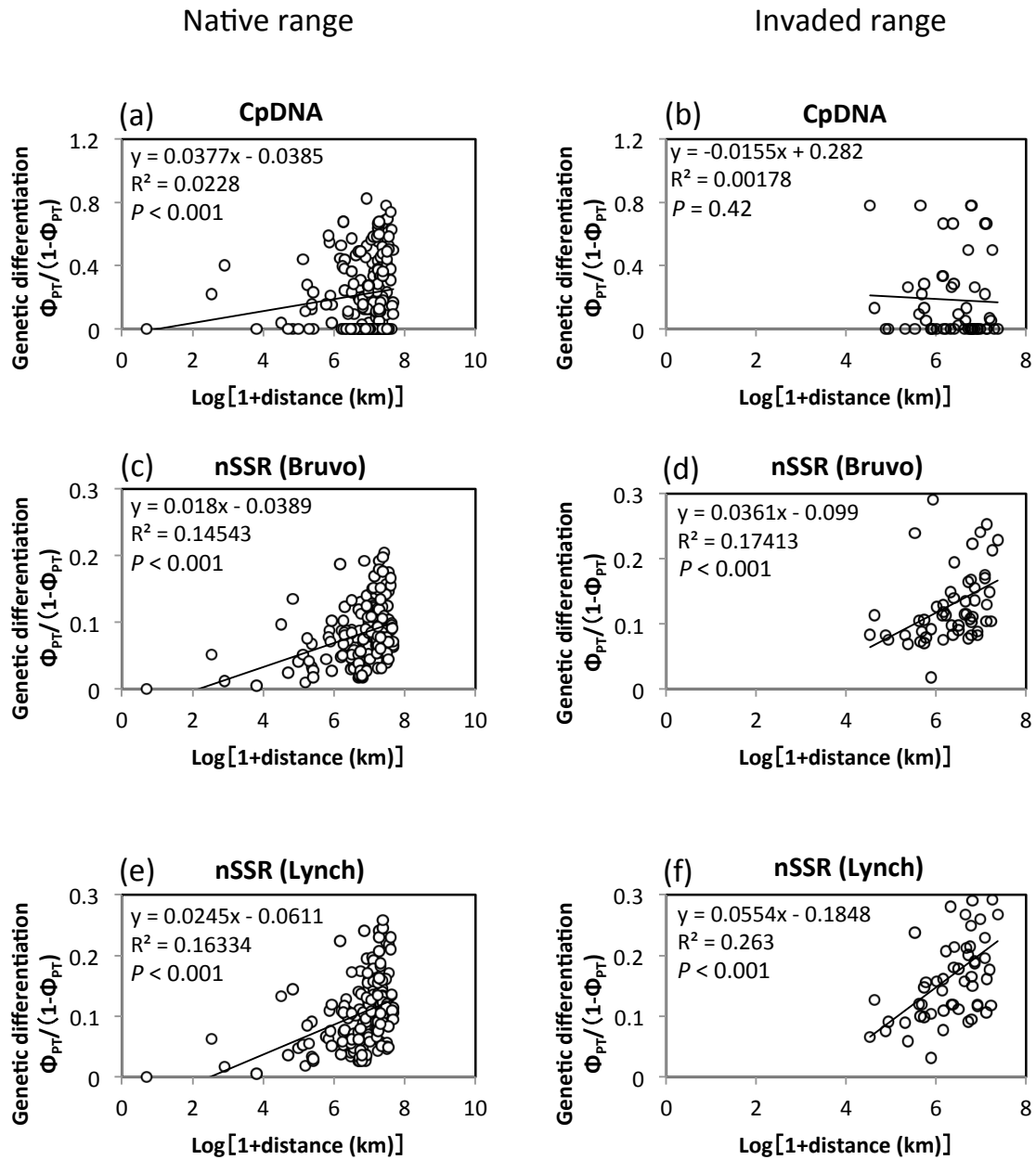
### Fig. 3

(a) Geographic distribution of the 27 chloroplast haplotypes found in *S. altissima* populations. H12 is observed in the tetraploid population EF. Haplotype names correspond to Fig. 1. (b) Geographic distributions of five nSSR gene pools estimated by STRUCTURE analysis (Pritchard et al. 2000). A neighbor-joining tree showing the relationships of each gene pool is depicted. The number of samples analyzed per population is proportional to the circle's size.

## Supplementary material

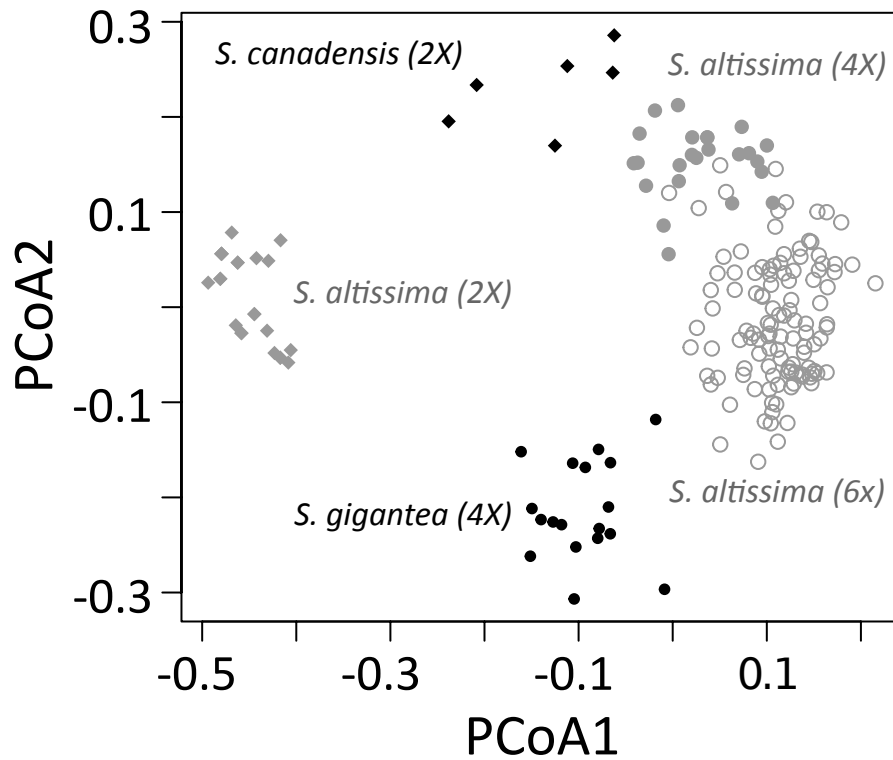
### **Multiple and mass introductions from limited origins: genetic diversity and structure of *Solidago altissima* in the native and invaded range**

Yuzu Sakata, Joanne Itami, Yuji Isagi, Takayuki Ohgushi



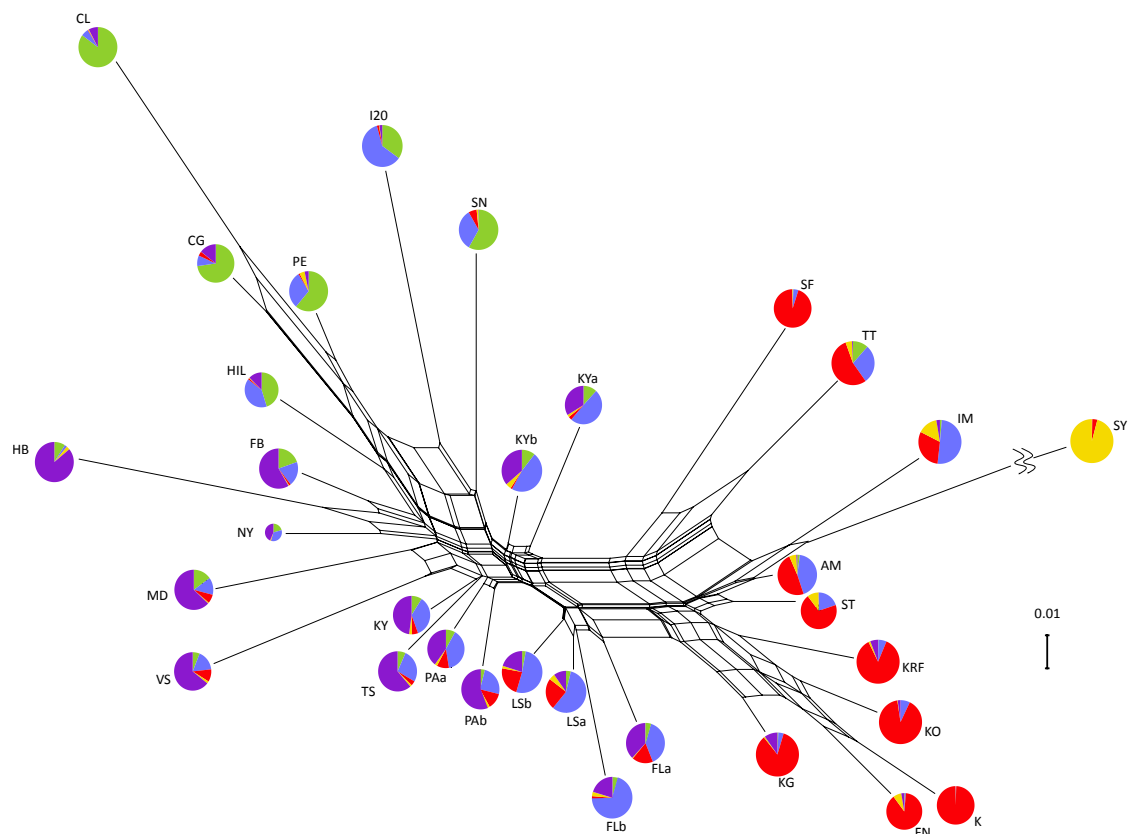
**Fig. S1**

Relationships between the pairwise genetic and geographic distance matrices obtained from (a), (b) CpDNA; (c), (d) Bruvo distance for nSSR; (e), (f) Lynch distance for nSSR.



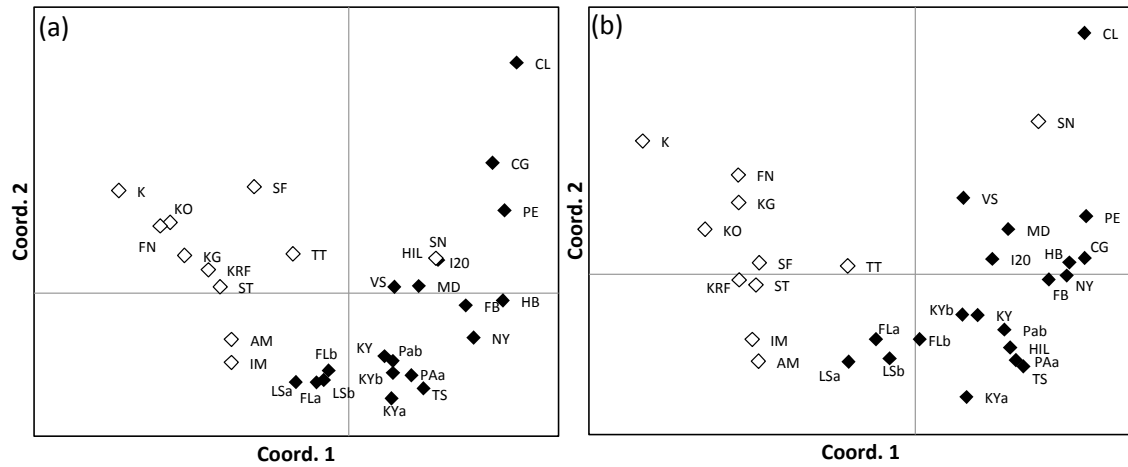
**Fig. S2**

Principal coordinate analyses of three different ploidy taxa of *S. altissima* (2X, 4X, and 6X) and two closely-related species (*S. gigantea* and *S. canadensis*). The first two principal coordinate axes are shown. Individuals of *S. altissima* are shown in grey, and other species are shown in black. Symbols represent different ploidy levels.



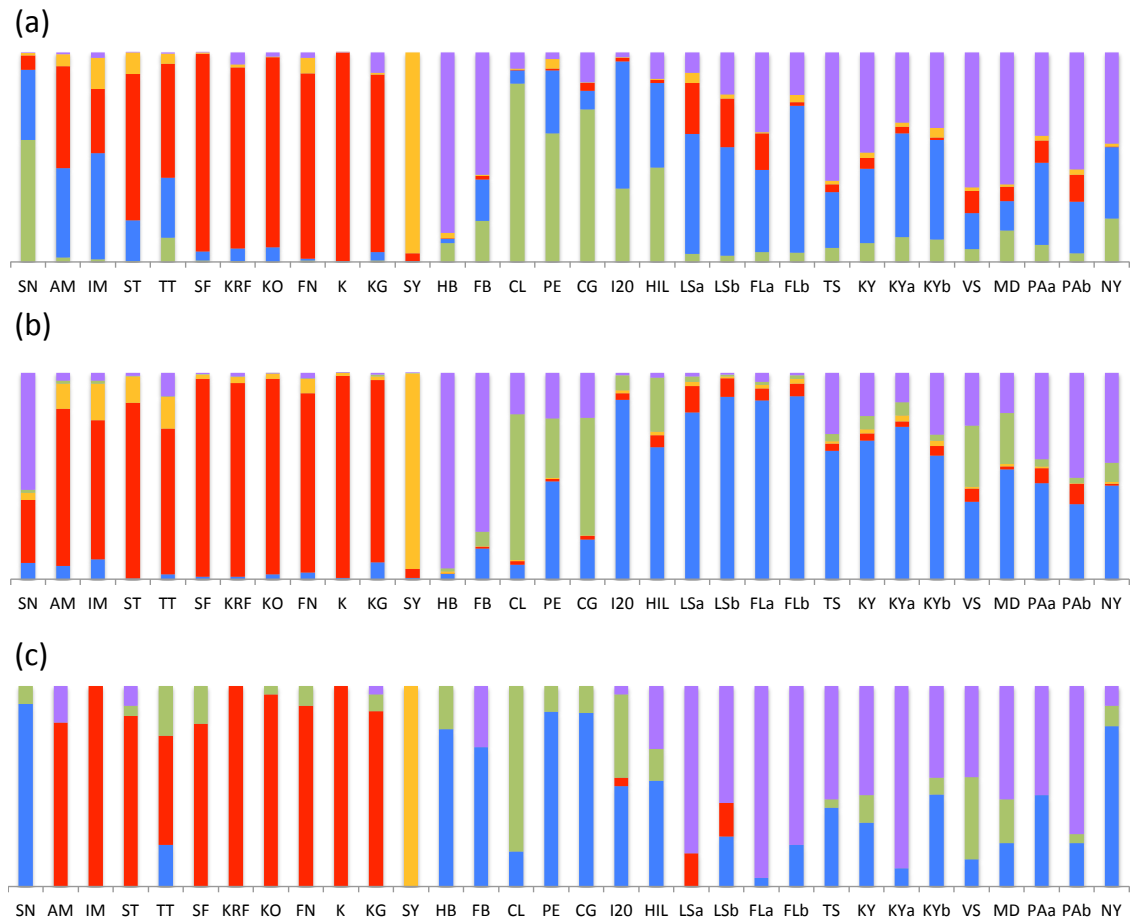
**Fig. S3**

Relationships among 32 *S. altissima* populations based on Nei's  $D_A$  (Nei et al. 1983), using a split network constructed by the neighbour-net method (Bryant and Moulton 2004) with the proportions of ancestry of each population superimposed at the node tips. Colors correspond with the result of the STRUCTURE analysis shown in Fig. 3b. Abbreviations refer to Table S1.



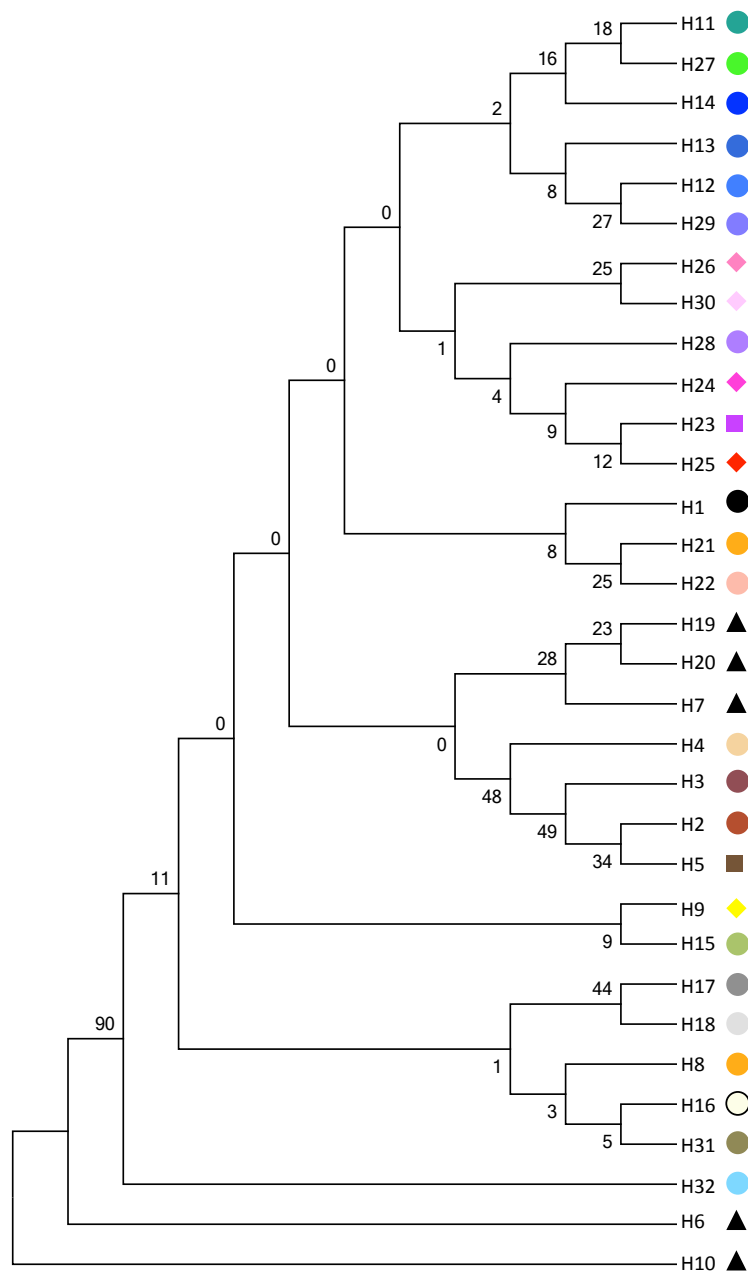
**Fig. S4**

PCoA based on pairwise  $\Phi_{RT}$  between the sampled populations of *S. altissima* using genetic distance of (a) Lynch and (b) Bruvo. Native and invaded populations are shown in closed and open symbols, respectively. Population abbreviations refer to Table S1.



**Fig. S5**

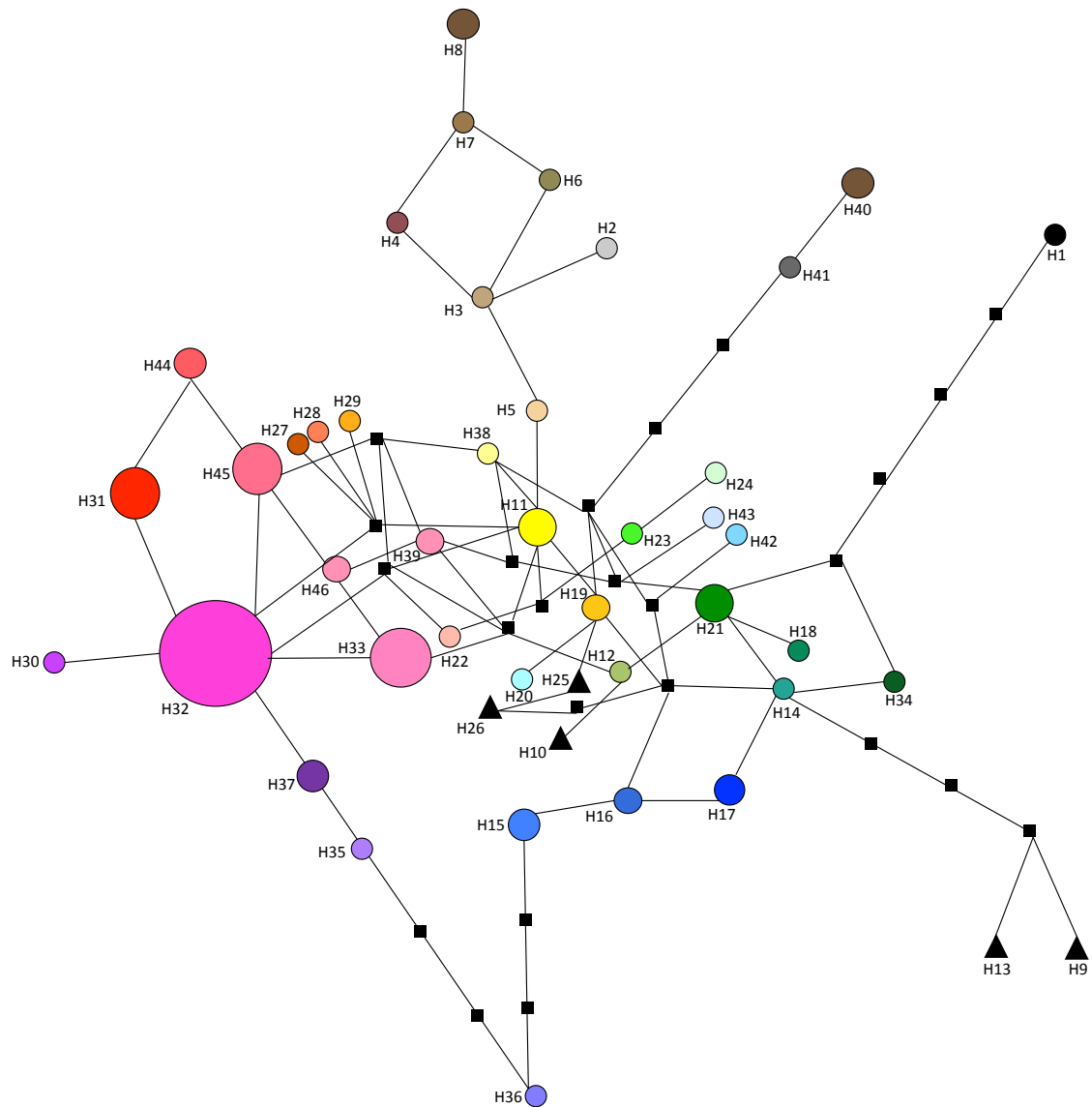
Probabilities of membership for each population to each of the five genetic clusters ( $K=5$ ) estimated by (a) the model-based clustering method STRUCTURE (Pritchard et al. 2000), (b) the spatial model-based clustering TESS analysis (Durand et al. 2009), and (c) the multivariate analysis that identifies and describes clusters of genetically related individuals DAPC (Jombart et al. 2010). Population abbreviations refer to Table S1.



**Fig. S6**

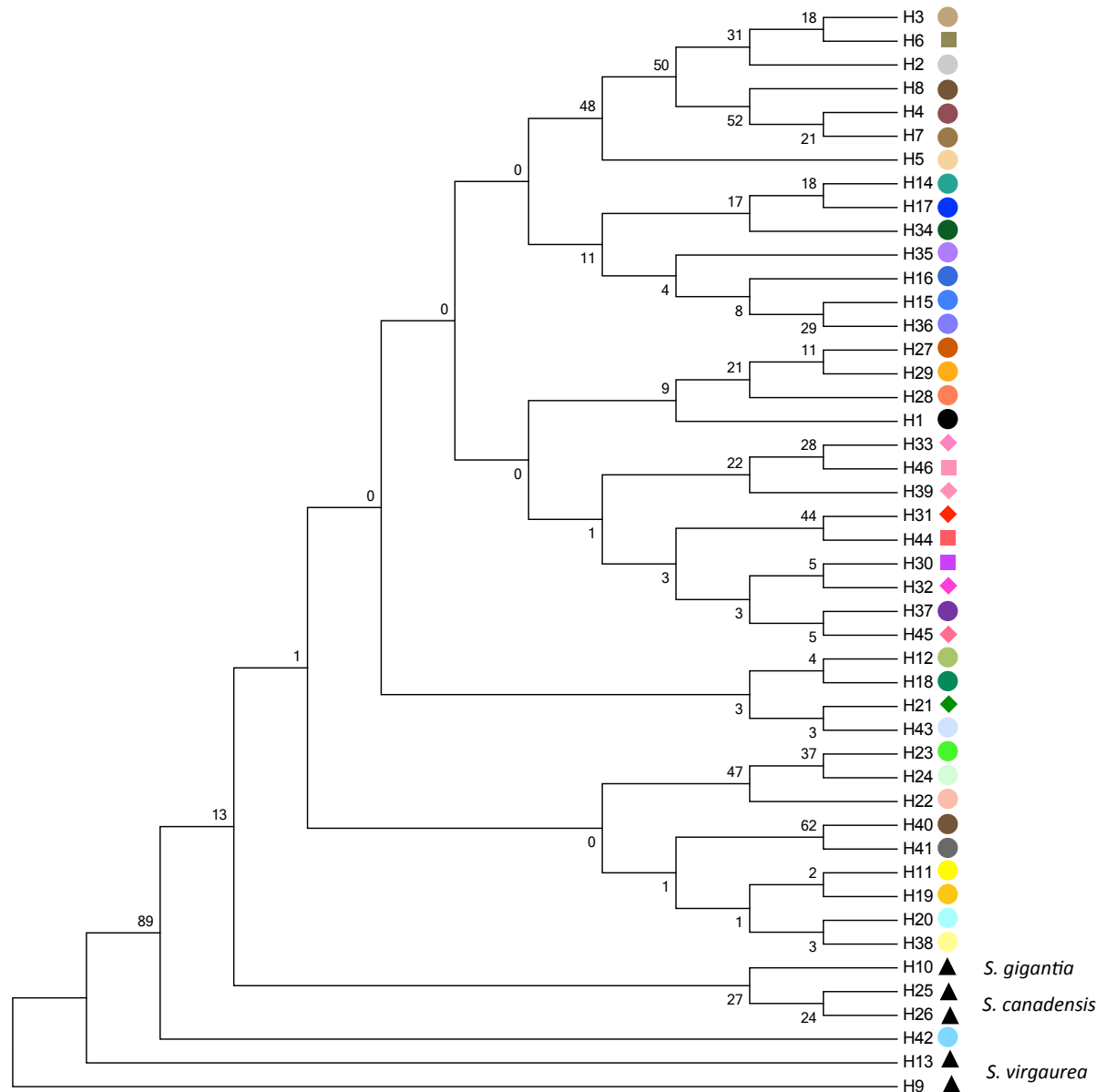
The inferred phylogenetic relationships among *S. altissima* chloroplast haplotypes and their relationship to outgroups reconstructed by maximum parsimony analysis based on the cpDNA sequence data. Bootstrap values are shown above branches. Haplotypes found in both native and invaded populations are shown in diamonds, and haplotypes only found in invaded populations are shown in squares, and haplotypes of other species are shown in triangles: *S. virgaurea*, H6 and H10; *S. gigantea*, H7; *S. canadensis*, H19 and H20.





**Fig. S7**

The haplotype network of *Solidago altissima* based on chloroplast DNA sequence variation including indels. Circle size is proportional to haplotype frequency. Each line between haplotypes corresponds to one mutational change. Small black squares indicate missing haplotypes. Haplotypes of outgroup species are shown in triangles: *S. virgaurea*, H9 and H13; *S. gigantea*, H10; *S. canadensis*, H25 and H26.



**Fig. S8**

The inferred phylogenetic relationships among *S. altissima* chloroplast haplotypes and their relationship to outgroups reconstructed by maximum parsimony analysis based on the cpDNA sequence data including indels. Bootstrap values are shown above branches. Haplotypes found in both native and invaded populations are shown in diamonds, and haplotypes only found in invaded populations are shown in squares, and haplotypes of other species are shown in triangles: *S. virgaurea*, H9 and H13; *S. gigantea*, H10; *S. canadensis*, H25 and H26.

## Supplementary material

### **Multiple and mass introductions from limited origins: genetic diversity and structure of *Solidago altissima* in the native and invaded range**

Yuzu Sakata, Joanne Itami, Yuji Isagi, Takayuki Ohgushi

Table S1. Distribution of sampling populations and indices of genetic diversity within populations of *S. altissima*.

Population	Location	Latitude	Longitude	<i>N</i>	<i>H</i>	<i>N<sub>a</sub></i>	<i>Ho</i>	<i>Shannon</i>
<i>Invaded range</i>								
SN	Hokkaido, JP	43.03N	141.30E	22	H:24,25,26	6.267	0.802	2.878
AM	Aomori, JP	40.82N	140.70E	22	H:23,24,25	8.467	0.932	3.028
IM	Iwate, JP	39.69N	141.12E	24	H:25,26	7.733	0.883	3.041
ST	Sado, JP	38.04N	138.44E	20	H:24,25	8.000	0.888	2.926
TT	Tokyo, JP	35.64N	139.58E	24	H:26	8.467	0.876	2.705
SF	Sizuoka, JP	35.13N	138.64E	21	H:9,24,25,26	9.000	0.900	2.912
KRF	Hyogo, JP	34.69N	135.26E	24	H:25	9.067	0.896	3.120
KO	Kochi, JP	33.56N	133.55E	24	H:5,25,26	8.133	0.895	2.694
FN	Fukuoka, JP	33.59N	130.21E	20	H:26	7.467	0.819	2.995
K	Kumamoto, JP	32.89N	130.73E	21	H:24,25	7.0000	0.880	2.306
KG	Kagoshima, JP	31.65N	130.42E	24	H:24,25,26,30	7.467	0.840	3.041
SY	Suncheon, KR	34.53N	127.30E	24	H:25	4.333	0.954	0.344
<i>Native range</i>								
HB	Minnesota, USA	47.39N	92.81W	23	H:2,3,9	7.933	0.904	2.368
FB	Minnesota, USA	44.23N	93.23W	23	H:18,25	9.533	0.896	2.894
CL	Iowa, USA	43.10N	93.45W	23	H:8,17,18,25	8.933	0.709	3.015
PE	Missouri, USA	39.78N	94.38W	23	H:8,9,24,26	8.933	0.829	2.645
CG	Kansas, USA	38.73N	96.48W	22	H:8,21,22	9.067	0.900	2.689
EF	Okulahoma, USA	35.45N	-95.88W	24	H:12	7.286	0.713	3.120
I20	Texas, USA	32.70N	96.58W	24	H:24,25	8.933	0.822	3.005
HIL	Texas, USA	32.00N	97.08W	19	H:25,28,29	8.267	0.890	2.552
LSa	Louisiana, USA	30.36N	91.15W	24	H:8,25	10.73	0.903	3.178
LSb	Louisiana, USA	30.34N	91.14W	24	H:4,25	11.13	0.899	3.178
FLa	Florida, USA	30.60N	84.38W	23	H:9,16,25	10.73	0.879	3.015
FLb	Florida, USA	30.50N	84.32W	24	H:25	10.13	0.876	2.925
TS	Tennessee, USA	35.23N	83.45W	23	H:9,25,26,27	10.26	0.882	2.955
KY	Kentucky, USA	36.82N	83.80W	22	H:13,25,32	10.46	0.874	3.028
KYa	Kentucky, USA	38.01N	84.51W	22	H:8,25	9.600	0.904	2.965

KYb	Kentucky, USA	37.05N	84.21W	24	H:8,25	10.20	0.868	3.178
VS	Virginia, USA	38.13N	78.45W	22	H:3,30	8.867	0.781	2.752
MD	Maryland, USA	39.07N	76.95W	23	H:11,13,14,25	9.933	0.796	2.789
PAa	Pennsylvania, USA	40.51N	75.79W	22	H:9,25	9.200	0.904	3.028
PAb	Pennsylvania, USA	40.54N	75.58W	23	H:3,8,14	11.00	0.894	3.135
NY	New York, USA	42.45N	76.48W	10	H:1,15,25	8.800	0.859	2.303
CA	California, USA	39.43N	-120.24W	24	H:31	2.500	0.528	2.658

$N$ , number of individuals;  $N_a$ , number of alleles per locus (mean across loci);  $H_o$ , gamatic heterozygosity (mean across loci) (Moody 1993); *Shannon*, Shannon diversity (mean across loci). EF is tetraploid and CA is diploid, and the rest of the population is hexaploid.

Table S2

Chloroplast DNA sequence polymorphisms detected in three non-coding regions of *S. altissima* and outgroup species identifying 32 haplotypes (H1–32). Accession numbers for the DNA sequences of outgroup species: Abbreviations: *n*, the number of samples assigned to particular haplotype.

		Nucleotide Position																GeneBank accession number																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																									
		<i>psbH-psbB</i>		<i>psbJ-petA</i>				<i>rpl-trnL</i>				<i>rps12-rpl20</i>		<i>rps16-trnK</i>						<i>trnQ-rps16</i>																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																							
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H11	1	T	C	C	G	A	C	C	G	T	A	C	G	C	A	C	T	G	C	T	G	C	AB907869	AB907901	AB907933	AB907965	AB907997	AB908029
H12	4	T	C	C	G	A	C	C	G	T	C	C	G	C	A	C	T	G	A	T	A	C	AB907870	AB907902	AB907934	AB907966	AB907998	AB908030
H13	2	T	C	C	G	A	C	C	G	T	C	C	G	C	A	C	T	G	A	T	G	C	AB907871	AB907903	AB907935	AB907967	AB907999	AB908031
H14	3	T	C	C	G	A	C	C	G	T	C	C	G	C	A	C	T	G	C	T	G	C	AB907872	AB907904	AB907936	AB907968	AB908000	AB908032
H15	1	T	C	C	G	A	C	T	A	T	A	C	G	C	A	C	T	G	C	T	G	C	AB907873	AB907905	AB907937	AB907969	AB908001	AB908033
H16	1	T	C	C	G	A	C	T	G	T	A	C	G	C	A	C	T	G	A	T	G	T	AB907874	AB907906	AB907938	AB907970	AB908002	AB908034
H17	1	T	C	C	T	A	C	T	G	T	A	C	G	C	A	C	T	A	A	T	G	C	AB907875	AB907907	AB907939	AB907971	AB908003	AB908035
H18	2	T	C	C	T	A	C	T	G	T	A	C	G	C	A	C	T	G	A	T	G	C	AB907876	AB907908	AB907940	AB907972	AB908004	AB908036
H19	1	T	C	C	G	A	C	T	G	T	A	C	G	T	A	C	T	G	A	T	G	C	AB907877	AB907909	AB907941	AB907973	AB908005	AB908037
H20	1	T	C	C	G	A	C	T	G	T	C	C	G	T	A	C	T	G	A	T	G	C	AB907878	AB907910	AB907942	AB907974	AB908006	AB908038
H21	2	T	T	C	G	A	C	T	G	T	A	C	G	C	A	C	T	G	A	T	G	C	AB907879	AB907911	AB907943	AB907975	AB908007	AB908039
H22	1	T	T	C	G	A	C	T	G	T	A	C	G	C	A	C	G	G	A	T	G	C	AB907880	AB907912	AB907944	AB907976	AB908008	AB908040
H23	1	T	T	C	G	A	C	T	G	T	A	C	G	C	A	C	T	A	A	G	G	C	AB907881	AB907913	AB907945	AB907977	AB908009	AB908041
H24	11	T	T	C	G	A	C	T	G	T	A	C	G	C	A	C	T	A	A	T	A	C	AB907882	AB907914	AB907946	AB907978	AB908010	AB908042
H25	58	T	T	C	G	A	C	T	G	T	A	C	G	C	A	C	T	A	A	T	G	C	AB907883	AB907915	AB907947	AB907979	AB908011	AB908043
H26	15	T	T	C	G	A	C	T	G	T	A	C	G	C	A	C	T	A	C	T	G	C	AB907884	AB907916	AB907948	AB907980	AB908012	AB908044
H27	1	T	T	C	G	A	C	C	G	T	A	C	G	C	A	C	T	G	C	T	G	C	AB907885	AB907917	AB907949	AB907981	AB908013	AB908045
H28	1	T	T	C	G	A	C	C	G	T	A	C	G	C	A	C	T	A	A	T	G	C	AB907886	AB907918	AB907950	AB907982	AB908014	AB908046
H29	1	T	T	C	G	A	C	C	G	T	C	C	G	C	A	C	T	A	A	T	A	C	AB907887	AB907919	AB907951	AB907983	AB908015	AB908047
H30	2	T	C	C	G	A	C	T	G	T	A	C	G	C	A	C	T	A	C	T	G	C	AB907888	AB907920	AB907952	AB907984	AB908016	AB908048
H31	4	T	C	C	G	A	C	T	G	T	A	C	T	C	A	C	T	G	A	T	G	C	AB907889	AB907921	AB907953	AB907985	AB908017	AB908049

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